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CODING GAINS FOR RANK DECODING

A. BRINTON COOPER III

FEBRUARY 1990

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Experimental data indicate that Chase's Rank Decoding algorithm, when used with simple parity check codes, provides values of coding gain from 2.0 to 4.0 dB.

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Contents

1 Soft Decision Concepts

In the transmission of binary information, a classical technique is for the receiver to subject the received waveform $v(t)$ to this threshold test:

if $v(t) > T$

then decide ONE was transmitted;

else decide ZERO was transmitted;

endif

This is an example of *hard decision* demodulation. By ignoring the actual value of the received waveform, hard decision actually discards useful information about the channel noise (or the "channel state"), for each symbol received.

It is well-known [1] that the use of channel state information can improve decoding reliability. This is because estimates of channel noise can be used to help identify which received symbols are most likely to be in error. Any technique which uses channel noise information to improve decoding is called a *soft decision decoding* algorithm [2]. Discarding channel state information in the decoding process requires an increase in the transmitter power required to achieve the same decoding error probability as when channel state information is used. The difference can be as much as 2 dB [1]. Much contemporary research in error control coding attempts to design soft decision algorithms and to evaluate the improvement in code performance which they provide [3–13].

Rank decoding [14] is a simple soft decision algorithm which is attractive because it is not terribly complex. It was originally incorporated into the design of a modem for high frequency communication channels. The modem design included a simple error control code and a decoding technique that takes into account the relative degrees of confidence in the hard decision values of the received binary symbols. Use of such relative values is computationally much less complex than estimating actual values. The present

work was undertaken to determine if this decoding algorithm has sufficient power to be useful on noisy channels and if it can be extended to iterated (product) codes.

A widely-used parameter for evaluating such codes is the *coding gain*, a measure of the savings in transmitter power provided by error control coding. Section 2 makes this concept mathematically more precise and discusses its correct application.

The original rank decoding algorithm and some extensions to the codes used by Chase are presented in Section 3. Section 4 discusses the experiment itself and its results. Significance of the results is discussed in Section 5 with a sketch of ongoing and additional work in Section 6.

2 Coding Gain

Many physical communication channels can be modeled accurately as the sum of a binary antipodal [1] signal [1] embedded in white, Gaussian (zero-mean), noise. This convention is followed here. The transmitted codeword is always the "all zero" codeword because the presence of a binary ONE in any position immediately indicates an error. This can be done with complete generality so long as the codes used are linear codes [15] whose words form an algebraic group [16]. Coding and decoding of [14] were used.

For binary antipodal signaling without coding, one information *bit* is carried by one transmitted *symbol*. The ratio E_b/N_0 of received signal energy per bit E_b to noise power spectral density N_0 determines the error probability per bit attainable by a perfect demodulator [1].

$$p = \frac{1}{2}(1 - erf(\sqrt{E_b/N_0})) \qquad (1)$$

This relation completely specifies the behavior of the channel with additive white Gaussian noise.

When pulses are transmitted at a constant rate, the received energy per bit E_b is directly proportional to the transmitter power and inversely

[1] ***Antipodal signals*** **belong to a set of two constant-valued waveforms having equal amplitudes and opposite signs and representing ONE and ZERO, respectively.**

proportional to the rate of transmission. The actual value of E_b is determined by physical parameters such as link distance, antenna directivity, and receiver gain, all of which are constant throughout this problem. When coding and/or nonbinary signaling are used on such channels, performance is evaluated by computing the error probability per received symbol as a function of the signal energy per received symbol[2]. This relation is compared with (1) to determine the degree of improvement, if any, afforded by the signal processing technique under study. That is, coding and decoding should lower the bit error probability when the transmitted power remains constant.

When a linear block code is used [15], additional (redundant) binary symbols are appended to each block of information bits. In order that the *information* transmission rate be the same with and without coding, the binary symbols with coding must be transmitted at a greater rate (*i.e.*, faster) than without coding. This requires an increase in the channel bandwidth. Since the noise power admitted to a model receiver is directly proportional to the bandwidth, the error probability per received symbol increases with bandwidth. However, E_b is unchanged. Therefore, the output error probabilty per bit (*i.e.*, the error probability delivered to the recipient of the data) tends to be reduced by coding, while the same error probability tends be *increased* by the increased bandwidth required by the coding itself.

In general, the ratio of the values of E_b/N_0 required to deliver equal error probabilities with and without coding is known as the *coding gain.*

With no coding, (1) represents the output error probability as a function of E_b/N_0 for a channel perturbed by white Gausian noise (WGN).

With coding, assume that information is transmitted at a constant rate R bits per symbol. Since more symbols are now used to represent the same information as in the uncoded case, $R < 1$. The received signal energy per symbol becomes [17] RE_b so that:

$$E_s/N_0 = R(E_b/N_0) \tag{2}$$

where

E_s = the signal energy per received symbol

[2]The reader is cautioned to distinguish between a *symbol*, which is a member of a transmission alphabet, and a *bit*, which is a unit of information [15].

R = the code rate in information bits per binary symbol.

From (1), the average error probability per received binary symbol is

$$p_s = \frac{1}{2}(1 - erf(\sqrt{E_s/N_0})) \quad (3)$$

Substituting (2) gives

$$p_s = \frac{1}{2}(1 - erf(\sqrt{RE_b/N_0})) \quad (4)$$

The decoder reduces p_s to the decoded error probability p_d.

The coding gain [15], then, is the ratio of E_b/N_0 without coding (1) to E_b/N_0 with coding when the value of p_d given by (1) is equal to that delivered by the decoder.

Note, because the error function $erf(x)$ cannot be inverted mathematically, it is customary to plot E_b/N_0 vs p for both the coded and uncoded cases on the same graph and to determine the coding gain graphically by examining the plot.

Without coding, $R = 1$ and $E_s = E_b$, making the coding gain unity (0 dB) as expected.

To evaluate the decoding algorithm under study, we simulated the decoder and experimentally estimated the relation between p_s and p_d. Coding gain was then determined as explained above.

Coding gain is not a universally applicable parameter. The conditions under which it is defined and the reference against which the "gain" is measured must be spelled out carefully in each specification. Its use for other than Gaussian channels has been forcefully argued [18].

3 Rank Decoding

Basically, the rank decoding algorithm [14] first decodes those received symbols which have the highest confidence values[3]. When a sufficient number of these have been decoded, they are used to decode other symbols having lower confidence values. At the second stage of decoding, the remaining low confidence symbols are decoded.

The rank decoding algorithm is applied to the simplest and most familiar of code designs. Four bits of information are written as a square array, and an even parity check is computed for each row and column of the array, resulting in a codeword of nine symbols (Figure 1). That is, *e.g.*,

$$i_1 + i_2 = p_1 \ (mod\ 2) \tag{5}$$

$$i_3 + i_4 = p_2 \ (mod\ 2) \tag{6}$$

$$p_3 + p_4 = p_5 \ (mod\ 2) \tag{7}$$

i_1	i_2	p_1
i_3	i_4	p_2
p_3	p_4	p_5

Figure 1: Codeword Design for Rank Decoding

The rate of this code is 4/9 (bits per binary symbol). These binary symbols are transmitted serially (one at a time) over a noisy channel. The receiver records the relative confidence of each symbol and makes a tentative (hard decision) estimate of its value (ZERO or ONE). Generally speaking, the rank decoding algorithm selects as candidate error locations those with the lowest confidence values.

Now, the actual algorithm[4] is simply stated:

[3]For many signals, confidence can be a monotone function of signal to noise ratio.

[4]It is enlightening to consider the hard decision decoding of this array. Hard decoding uses the fact that each row or column can yield only one piece of information: whether

INIT: Place the received symbols in an array corresponding to Figure 1. Check parity of each row and column. Rank (order) each received symbol according to its confidence value. Mark with a FLAG each of the 3 weakest symbols. (Note that each symbol is contained in two parity check equations.)

STEP_1: Examine the symbol of highest rank.

a. If both equations check, decode the symbol as received. That is, assign as its permanent value the temporary hard decision value assigned initially by the receiver.

b. If both equations fail to check, flag the symbol.

c. If only one checks, decode it as received provided there is an undecoded symbol with lower rank in each equation (*i.e.*, in the row and column containing the position under consideration). Flag these lower-ranked symbols if not already flagged.

STEP_2: After decoding a symbol, if any check equation contains only one undecoded symbol, *decode it by forcing parity to check*.

STEP_3: When all undecoded symbols have been flagged, decode the one with largest rank, and do Step 2.

This decoding algorithm works because the parity check equations have the *orthogonality* property:

> There is an integer J such that every information position i_j appears in a set of J or more parity check equations and that no other information position i_k, $k \neq j$ appears in more than one of any such set of J equations.

The significance of orthogonality is that an error in a position such as i_k affects only one parity check on i_j. By itself, such an error can render only

or not parity checks. If a single binary symbol of the nine was inverted by noise, the parity checks on its row and column will fail to check, and the decoder can determine with certainty which position is in error. However, if any two symbols are inverted by noise, two rows or two columns (or both) will fail, indicating either two or six possible error locations.

one the parity checks incorrect. Each additional error position makes one additional parity check fail. Thus, only when more than half of the I_k are in error will incorrect decoding of an information position occur. Since there are $J = d - 1$ such checks, this is tantamount to there being more than $(d-1)/2$ errors. Otherwise, taking a majority vote of the values afforded by J orthogonal checks on an information position will give the correct value in that position.

"Good" codes having orthogonal parity checks have been sought precisely because of ease in decoding [19].

In particular, as we shall discuss later, the coding gains of *self-orthogonal array codes*, of which Figure 1 is an example, should be examined under rank decoding.

4 The Experiment

The all-zero codeword is assumed to have been transmitted. Channel errors are simulated by drawing random numbers from a zero-mean, Gaussian distribution. These numbers are added to the transmitted antipodal signal to simulate the analog value of the received signal. The tentative hard decision value is taken to be binary ONE if the random value is positive and ZERO otherwise.

The decoding algorithm was used to sort the received symbols by absolute value in order to determine the confidence which the decoder places in them. Those with smallest absolute value are the most difficult to classify unambiguously as ZERO or ONE because the values are nearest to the decision threshold. The decoding algorithm is applied to this data, producing a table of channel error probability vs decoded error probability over a wide range of values of channels. Each pair of values was determined from approximately 100,000 transmitted symbols.

The error probabilities with and without decoding were estimated by dividing the numbers of errors before and after decoding by the total number of symbols transmitted. (Recall that the parity check symbols, too, are decoded.) Signal to noise ratios that would produce these probabilities

without and with coding, respectively, were estimated from (1) and (4). The measured coding gain is computed (see above) as the reduction in signal to noise ratio afforded by the coding for fixed output error probability.

Representative sets of data from some of the simulations are presented in Table 1.

Rate 4/9 Code				Rate 9/16 Code			
Ch Ers	Dec Ers	p	p_d	Ch Ers	Dec Ers	p	p_d
19213	14154	0.213499	0.157282	29875	25906	0.186737	0.161929
16804	11083	0.186730	0.123157	25476	20052	0.159241	0.125338
14310	8098	0.159016	0.089987	21070	14440	0.131701	0.090259
11814	5298	0.131280	0.058873	16747	9291	0.104679	0.058075
9355	3291	0.103955	0.036570	12749	5433	0.079689	0.033960
7148	1823	0.079430	0.020258	9200	2505	0.057506	0.015658
4608	670	0.057606	0.008376	6123	905	0.038273	0.005657
3050	205	0.038129	0.002563	3707	277	0.023171	0.001731
1887	57	0.023590	0.000713	2069	53	0.012933	0.000331
1044	18	0.013051	0.000225	979	9	0.006119	0.000056

Table 1: Rank Decoding Data for Two Cases

5 Comparisons and Conclusions

As shown in a previous chapter, codes originally used for rank decoding were constructed from a single parity check on two information bits. The present work considers additional constructions from a single check on three and four information bits as well. For example, the constituent parity check equations for the 4x4 code (rate = 9/16) are of the form

$$i_1 + i_2 + i_3 = p_1 \tag{8}$$

and there are four such equations. As the length of the codeword grows, so does the code rate R. But since a single parity check symbol is called upon to protect more information, the amount of protection per bit decreases.

Simulations were run for the original case with a code rate of 4/9, and for codes with nine information positions and a code rate of 9/16.

The output error probability as a function of E_b/N_0 is plotted in Figure 2 for the uncoded case (used as a standard for comparison) and for the two codes studied. The coding gain as a function of output error probability for the 3x3 code is presented in Figure 3. The coding gain varies from 2 to 4 dB.

Although the differences are small, the data show that the coding gain decreases slightly with code length for the three cases studied. This indicates that admitting additional noise by widening the receiver bandwidth to accommodate coding has paid off in a reduction in transmitter power for the same output error probability provided by an uncoded signal.

Positive values of coding gain were achieved on channels having error probabilities of 0.10 and below. While this is helpful, there are codes available which have larger values of coding gain [20]. Still, these results indicate that rank decoding of more powerful codes might provide a simple method of using soft decision decoding to achieve useful values of coding gain.

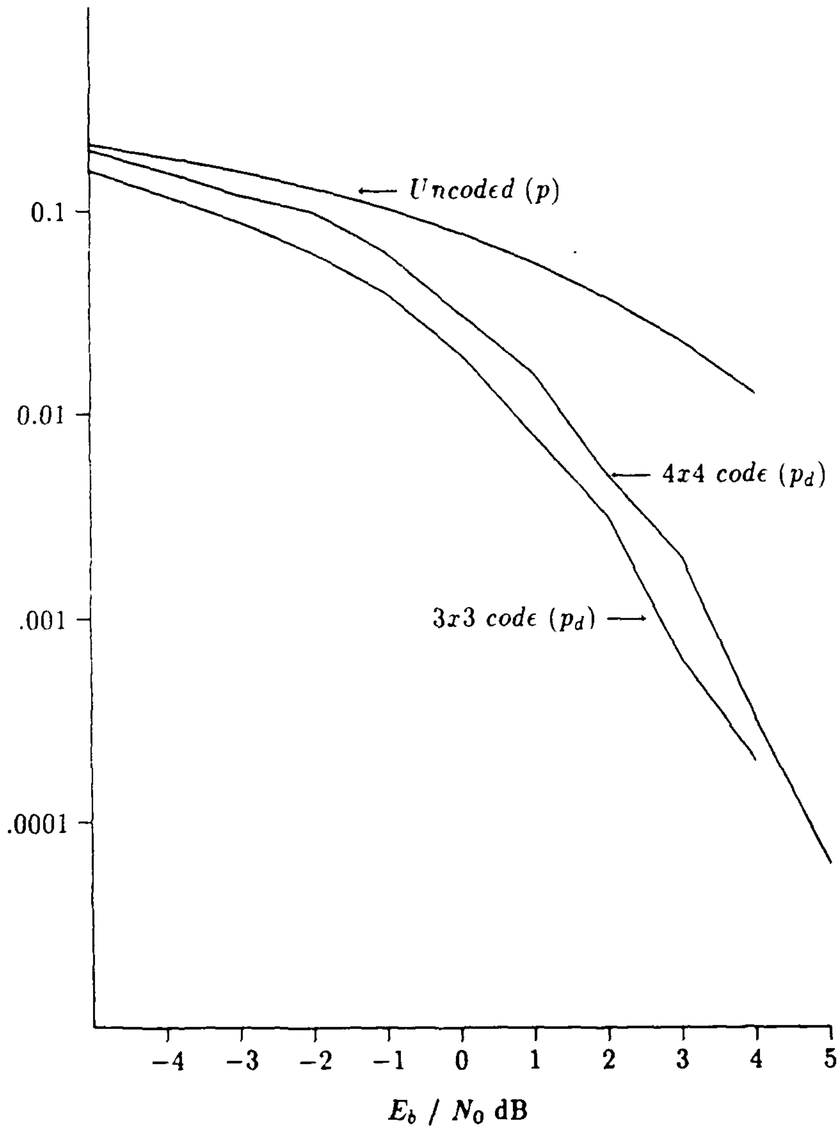

Figure 2: Error Probability vs Signal to Noise Ratio

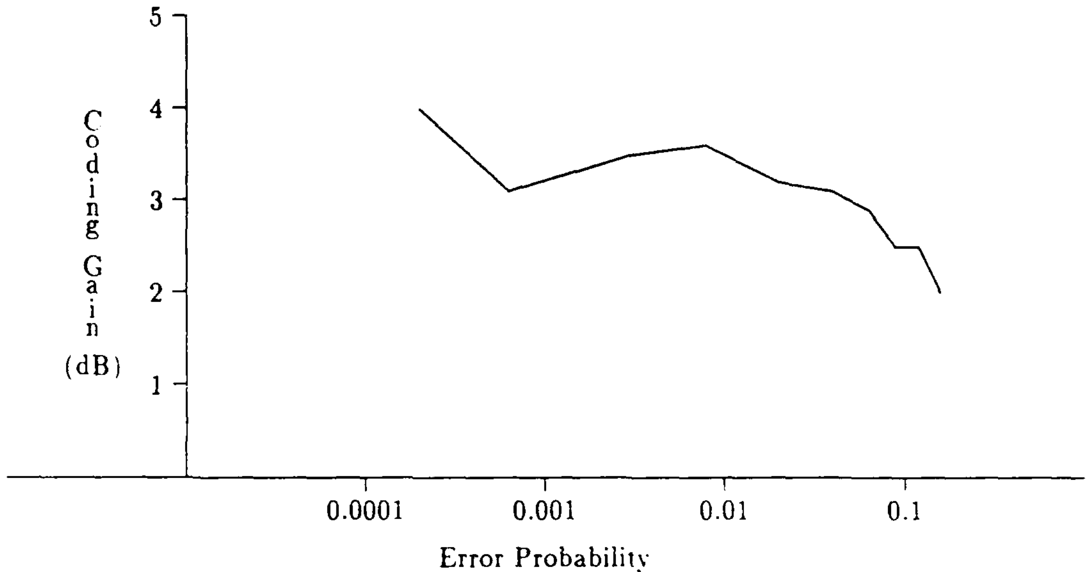

Figure 3: Coding Gain vs Error Probability

6 Continuing Research

The power of these codes (with $R \geq 0.44$) to correct errors is quite limited, being based upon a simple parity check in each row and column. Adaptation of rank decoding to iterations of lower rate but more powerful codes will be investigated. This may require a significant modification to the decoding algorithm, however, if the consituent codes do not have sets of orthogonal parity checks.

Self-orthogonal array codes [21], of which the simple parity check codes in these experiments are an example, have the orthogonality property required by the rank decoding algorithm and seem to have a structure for applying this algorithm to their decoding. Since more than two parity check equations can be written for each information position while the code rate can remain at 0.5, the promise for useful values of coding gain is strong. Work on refining a decoding algorithm in order to achieve these results is continuing.

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